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IAEA Facility-Level Safeguards and Implementation and Advanced Verification Technologies

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Changing the World's Energy Future

Mark Schanfein

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Safeguards Summer VTC Lecture Series
August 2021

Mark Schanfein, Idaho National Laboratory

A High-Level View of IAEA Safeguards

STATE LEVEL CONCEPT
Correctness and Completeness

(Declared/Undeclared Facilities and Activities)

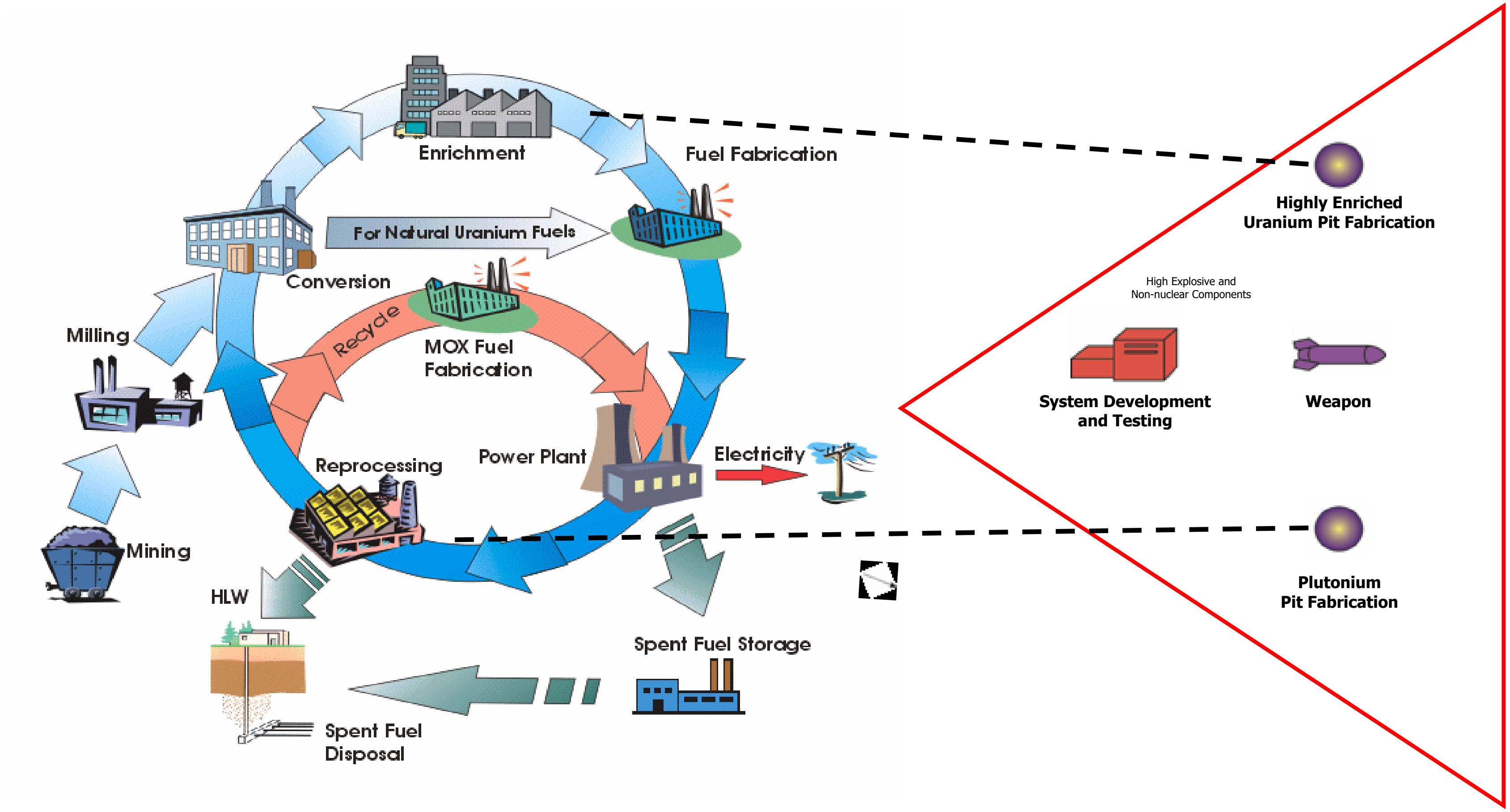
- INFCIRC 153/66
- SSAC (domestic)
- Reporting
- Design Information
- Facility Attachment
- Inspections

(Undeclared Facilities and Activities)

- INFCIRC 540
- Provision of Information
- Complementary Access
- Open Source Analysis
- Satellite Image Analysis
- Third Party Information

1. Non-diversion of nuclear material (detection of diversion: abrupt and protracted) at declared facility
2. Absence of undeclared production or processing of nuclear material at declared facilities (detection of misuse)
3. Absence of undeclared nuclear material or activities

Production of Weapons Usable Material → State Acquisition Pathway Analysis (APA)



Model Comprehensive Safeguards Agreement – IAEA INFCIRC/153

Establishes:

- The application of Safeguards on all Source and Special Fissionable Material (in all peaceful nuclear activities)
- That nuclear safeguards shall be based on **Cooperation** between the State and the IAEA
- That a State-System of Accounting for, and Control of all Nuclear Material (SSAC) shall be established – i.e. basis for National Nuclear Safeguards
- That the State shall provide safeguards relevant Information to the IAEA in order to implement effective safeguards
- The starting point of safeguards and when safeguards can be terminated
- The objective of International Nuclear Safeguards
- Subsidiary Arrangements
- The use of Nuclear Material Accountancy as the fundamental safeguards measure
- The use of Containment and Surveillance (C/S), and other supportive measures, etc.

Subsidiary Arrangements to the Safeguards Agreement (General Part and Facility Attachments)

- Subsidiary Arrangements to the Safeguards Agreement are concluded between the State and the IAEA
- These contain the administrative and technical procedures that specify how the provisions in the Safeguards Agreement shall be applied
- They consist of a General Part applicable to all nuclear activities in the State
- They also include Facility Attachments, which are specific to each nuclear facility or group of collocated facilities

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INFCIRC/153 – The Structure & Content of Agreements Between the Agency & States in Connection with the NPT

- Guidance to the IAEA and State:

  PART I, paragraph 4, The Agreement should provide that safeguards shall be implemented in a manner designed:

  - (a) To avoid hampering the economic and technological development of the State … in the field of peaceful nuclear activities, including international exchange of nuclear materials;
  - (b) To avoid undue interference in the State’s peaceful nuclear activities, and in particular in the operation of facilities; and
  - (c) To be consistent with prudent management practices required for the economic and safe conduct of nuclear activities.

Facility Attachments

- Facility Attachments specify the details regarding **what** facility data can be collected, **how** it can be collected, the types of facility instruments that can be used by IAEA inspectors, working hours for inspections, escort requirements, etc.

- Although some limitations may be imposed by the Facility Attachment, the IAEA must still be able to draw an Independent Safeguards Conclusion, regarding the nuclear material and facilities in the State

Facility Attachment for RRCA

1. Identification of the facility
2. Information on the facility
3. Safeguards measures
4. Specifications for Material Balance Areas and Key Measurement Points
5. Records system
6. Reports system
7. Inspections
8. Agency statements

SG Implementation Statistics for 2019 (2016 Statistics)

• Number of facilities & LOFs under SG:	1,324 (1,290)
• Number of States where SG applied:	184 (181)
• Nuclear material under Safeguards:	216,448 SQs (204,073)
• Number of Inspections:	2,953 (2,216)
• Number of Calendar Days in Field:	13,140 (13,275)

Regular Budget: €142.9 million; Extrabudgetary: €20.2 million

(2016 Regular Budget: €133 million; Extrabudgetary: €30 million)

The Safeguards Agreement – (INFCIRC/153), para. 28

The Objective of Safeguards:

- "…the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons, or of other nuclear explosive devices or for purposes unknown, and the deterrence of such diversion by the risk of early detection."

Key Words and Phrases:

- Timely Detection of Diversion
- Significant Quantities of Nuclear Material
- Deterrence by the Risk of Early Detection

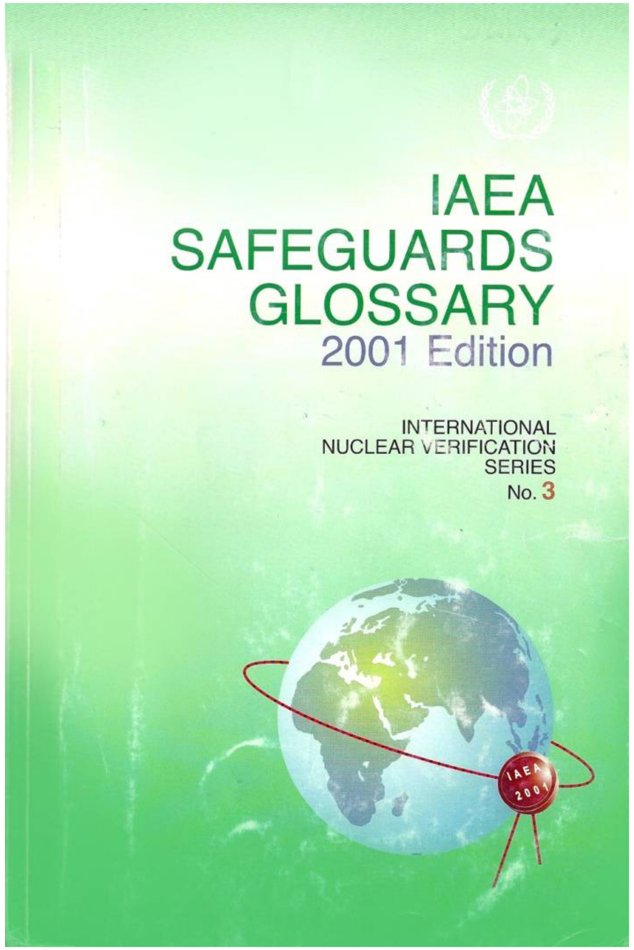
Other Key Terms and Concepts:

- Other relevant terms are defined on the following slides based on the IAEA Safeguards Glossary – (See the IAEA Glossary for more details)

Safeguards Glossary

Interpreting IAEA Safeguards
Terms, Definitions, and Concepts

https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf



The Goals of Safeguards

Significant Quantities of Nuclear Material:
(Source - IAEA SG Glossary 2001 Ed., Table-II Significant Quantities)*

Nuclear Material	Significant Quantity
• Plutonium†	8 kg Pu
• U-233	8 kg ^{233}U
• HEU (U-235 ≥ 20%)	25 kg ^{235}U
• LEU, Natural, Depleted U	75 kg ^{235}U‡
• Thorium	20 tonnes Th

* Approximate amount of nuclear material for which the possibility of **manufacturing** a nuclear explosive device cannot be excluded

† For Pu containing less than 80% ^{238}Pu

‡ Or 10 t natural U or 20 t depleted U

Did You Know?

According to the International Atomic Energy Agency (IAEA), 25 kg of HEU (about the size of a grapefruit) or 8 kg of plutonium (about the size of a soda can represent a “significant quantity” required to make a crude nuclear weapon.

Direct/Indirect Nuclear Material

- Direct Use Material
  - Can be manufactured into a nuclear explosive devise without transmutation or further enrichment
    - Pu (<80% ^{238}Pu)
    - HEU (>20% ^{235}U)
    - ^{233}U
- Indirect Use Material
  - All other nuclear material
    - LEU, NU, DU (<20% ^{235}U)
    - Th

The Goals of Safeguards

Timeliness of Detection:
(Source - IAEA SG Glossary 2001 Ed., Table-I and para. 3.20)*

Nuclear Material	*Historical* IAEA Timeliness Goal**
• Plutonium (unirradiated)	1 Month
• U-233 (unirradiated)	1 Month
• HEU (U-235 > 20%) (unirradiated)	1 Month
• Pu, U-233, and HEU (irradiated)	3 Months
• LEU, Natural, and Depleted-U	1 Year
• Thorium	1 Year

* Timeliness Detection Goal is based on the **time to convert** the nuclear material to finished metallic components (suitable for fabricating nuclear weapons)
** Can be relaxed under State Level Concept

The Objective of Safeguards (continued)

Deterrence by the Risk of Early Detection:

- **Facility Inspection Frequencies and Verification Requirements are established on the safeguards approach**
- **The inspection frequencies are designed to allow the IAEA to meet the Timeliness Goals for Detecting a possible Diversion***

Facility Type	*Historical* Interim Inventory Verification*
Research Reactor	Quarterly or Annually
LWR	Quarterly
Uranium Enrichment Plant	Monthly
Spent Fuel Reprocessing	Monthly
PuO_2/MOX Fabrication	Monthly

* These are historical examples, the frequency will vary depending on whether the State is under Integrated Safeguards through the State-Level Concept

Types of Safeguards Inspections

- ***Ad hoc inspections*** - typically are made to verify a State's initial report of nuclear material or reports on changes thereto, and to verify the nuclear material involved in international transfers (usually prior to the entry into force of the Facility Attachment).

- ***Routine inspections*** - frequently used - The Agency's right to carry out routine inspections under the Comprehensive Safeguards Agreements is limited to those locations within a nuclear facility, or other locations containing nuclear material, at agreed strategic points. May be carried out according to a defined schedule or they may be of an unannounced or short-notice character (para. 84, INFCIRC 153).

- ***Special inspections*** – rarely used - carried out in circumstances according to procedures laid down in para. 77 (INFCIRC 153). The IAEA may carry out such inspections:
  - in order to verify information in special reports, or
  - if it considers that information made available by the State concerned, including explanations from the State and information obtained from routine inspections, is not adequate for the Agency to fulfill its responsibilities under the safeguards agreement.

Inspections Activities

Activities performed by IAEA inspectors during and in connection with on-site inspections at facilities may include:

- **Auditing the facility's accounting and operating records and comparing these records with the State's accounting reports to the Agency**
- **Verifying the nuclear material inventory and inventory changes**
- **Taking environmental samples**
- **Applying containment and surveillance measures**

Safeguards Visits

Safeguards visits may be made to facilities and States at agreed times for purposes other than inspection or complementary access (CA):

- To carry Design Information Examination and Verification (DIE/DIV) during the entire lifecycle of a facility
- For fact finding
- For technical discussions in connection to developing a Safeguards Approach
- To negotiate and discuss with the facility and State regarding safeguards implementation

Accountancy Structure

- **Material Balance Area (MBA)**
- **Flow Key Measurement Points (FKMP)**
- **Inventory Key Measurement Points (IKMP)**
- **[Other Strategic Points (OSP)]**

Accountancy Structure: MBA

- **Material Balance Areas (MBA)**
  - **To determine the quantity of material transferred into and out of; and**
  - **To determine the book and physical inventory within**
  - **May be an accountancy area for Material Unaccounted For (MUF) or Shipper/Receiver Difference (SRD)**

Accountancy Structure - FKMP

- Flow Key Measurement Points (FKMP)
  - Locations where Inventory Changes (IC) can be measured
    - Operator declaration
    - Inspector verification
  - Usually flow across MBA boundaries, but not always.
  - Examples:
    - Receipts and Shipments
    - Nuclear Loss and Gain
    - Accidental Loss or Gain
    - Transfers-to and Retransfers-from Retained Waste
    - Measured Discard
    - Exemption and De-exemption of nuclear material
    - Termination of safeguards for non-nuclear use

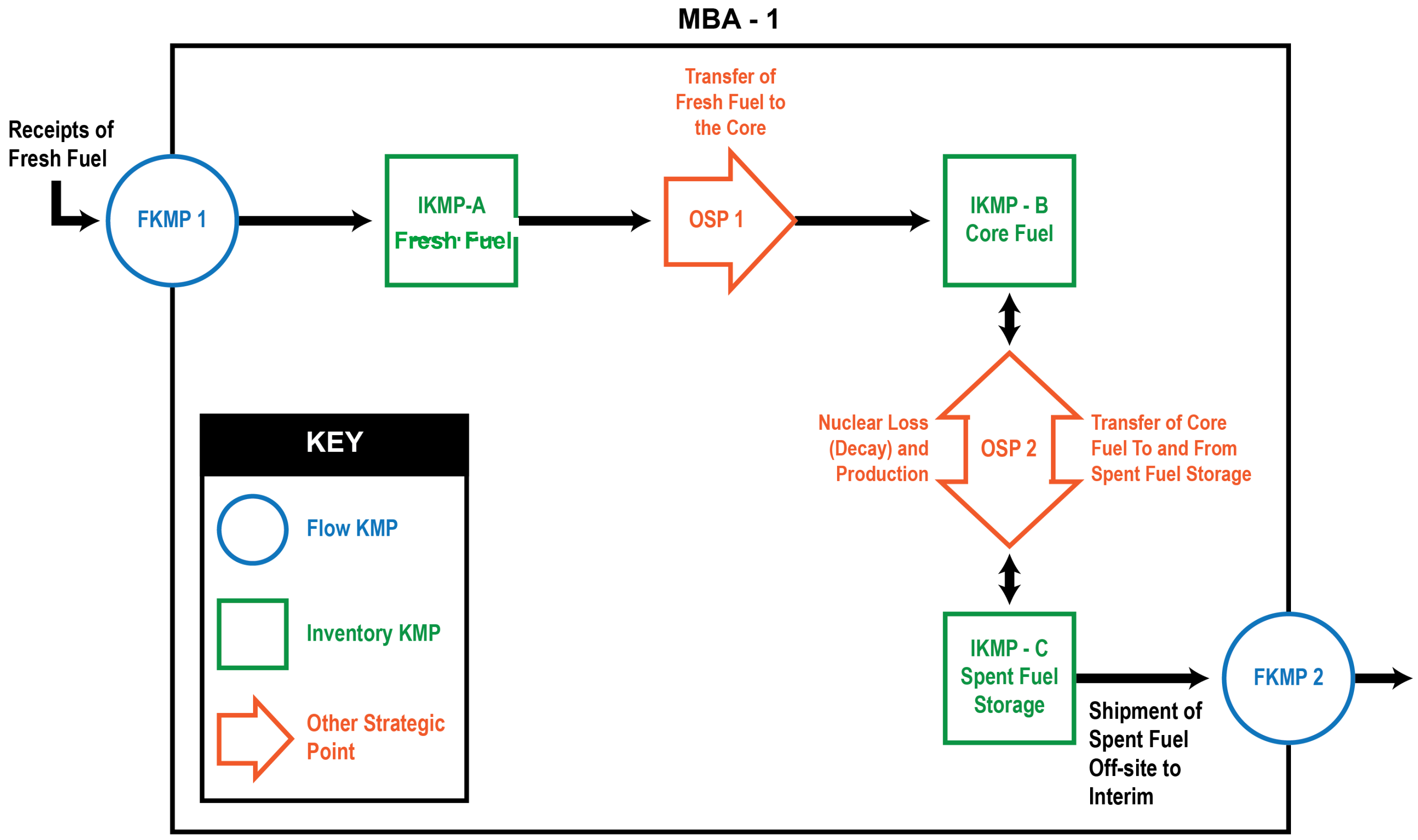
Accountancy Structure - IKMP

- Inventory Key Measurement Points (IKMP)
  - Locations where Interim and Physical Inventory Verification (IIV/PIV) can be carried out
    - Operator declaration
    - Inspector verification
  - May have more than one IKMP in an MBA.
  - Material within usually has similar characteristics or measurement requirements.

Support to Accountancy Structure - OSP

- **Other Strategic Points (OSP)**
  - ➢ **<u>Supports</u> Accountancy Measures**
    - **Provides Continuity of Knowledge (CoK)**
    - **Containment/Surveillance (C/S)**
    - **Monitoring**
  - ➢ **Provides Added Assurance**
    - **Short notice check of operator measurement systems.**
    - **Verification of flow within the MBA.**
    - **Verification of operational status.**

Nuclear Material Balance Area (MBA), Key Measurement Points (KMPs), and Other Strategic Points (OSP)



IAEA Facility-Level Safeguards and Implementation

Material Balance Equation:

- **Material Unaccounted For (MUF)**
  - **Beginning Book Inventory (BBI)**
    + Increases – Decreases
    = Ending Book Inventory (EBI)
  - **EBI – Physical Inventory Taking (PIT) = MUF**

- **IAEA performs a Physical Inventory Verification (PIV)**

Item Facility is a Facility Where:

- All nuclear material is kept in item form
- The integrity of the item remains unaltered
- Such as:
  - Reactors
  - Critical assemblies
  - Laboratories
  - Storages
- MUF = 0, expectation

Bulk Facility is a Facility Where:

- **Nuclear material is held, processed or used in bulk form, i.e., pellets, powders, liquid, gas**
- **Facility may be organized in multiple material balance areas (MBA)**
- **Such as:**
  - **Conversion**
  - **Enrichment**
  - **Fuel fabrication**
  - **Reprocessing**
  - **Storages**
- **MUF ≠ 0, Verify if Statistically/Safeguards Significant**

Other Important Safeguards Terms and Concepts *(INFCIRC/153 and IAEA Safeguards Glossary)*

Nuclear Material Accountancy
- The practice of nuclear material accounting, as implemented by the Facility Operator and the State System of Accounting for and Control of Nuclear Material (SSAC), that satisfies the requirements in the Safeguards Agreement between the State and the IAEA

Verification Operator's Accountancy System
- Is used to independently verify the correctness of the information in the Facility Operator's Records and the State Reports submitted by the SSAC to the IAEA
- Is based on the declaration of nuclear material and activities made by the Facility Operator
- The Facility Operator's declarations are verified by the IAEA using inventory taking and **statistically based random sampling** during inspections
- Verification techniques include: Destructive Analysis (DA), Non-Destructive Analysis (NDA), etc.

Random Statistical Sampling

- Confidence Level = 20%, 50%, 90%
- Pu Significant Quantity (Goal Qty) = 8 kg
- Population = N
- Average mass = $\boldsymbol{m}_{avg}$
- Sample = n

Inventory Stratum – 1

m_{avg}=8g, N=1000, n=?

Inventory Stratum – 2

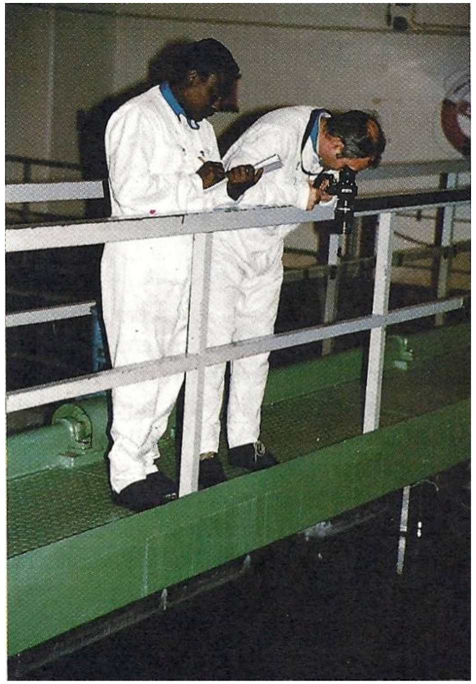
m_{avg}=800g, N=100, n=?

Nuclear Material Verification (The Short Version)

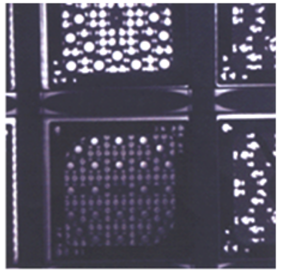
- The State (SSAC) declares nuclear material inventories and inventory changes at facilities to the IAEA
- The IAEA verifies the State’s and Facility Operator’s declarations through safeguards inspections
- The IAEA verifies these declarations using Safeguards Techniques
  - Bookkeeping (Audit of Records and Reports)
  - Verification of Nuclear Material Inventory and Changes
  - Containment and Surveillance (to support Accountancy)
  - Other Measures as required

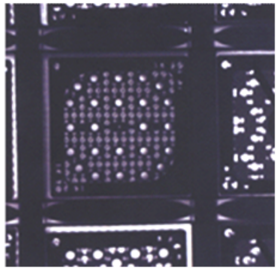
Nuclear Material - Inspection and Verification

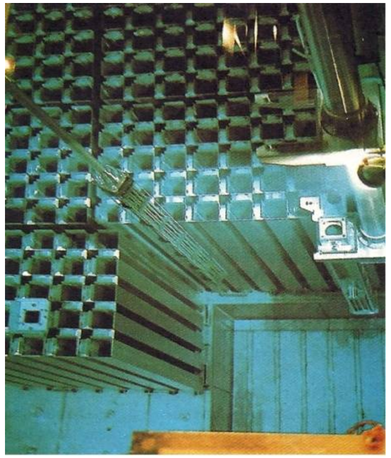
(Source – IAEA, ca. 2008)



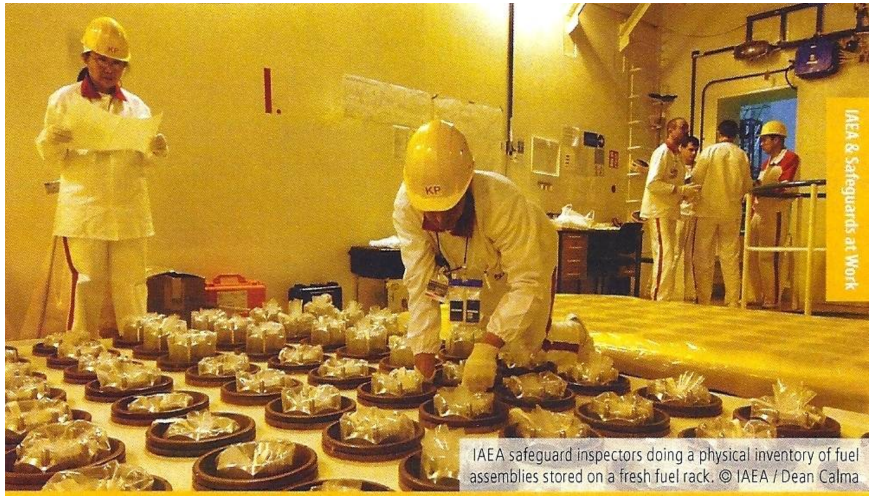
IAEA Inspectors Using CVD



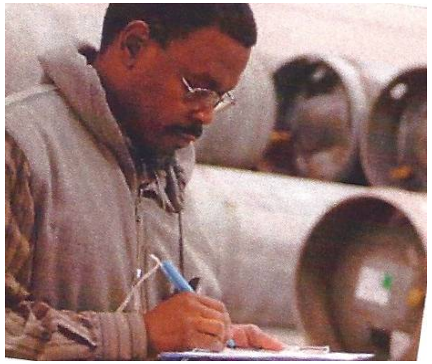




Ringhals PWR Storage Racks



IAEA safeguard inspectors doing a physical inventory of fuel assemblies stored on a fresh fuel rack. © IAEA / Dean Calma



Other Important Safeguards Terms and Concepts *(INFCIRC/153 and IAEA Safeguards Glossary)*

Nuclear Material Accountancy – Nuclear Material Verification

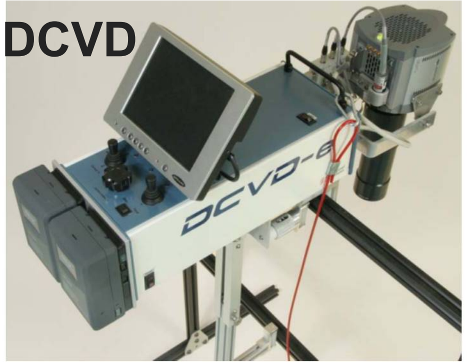
- For the purpose Verifying Inventory and Inventory Changes nuclear material is sorted into strata
- Using statistically based sampling to verify the material type and quantity,
  - Samples are taken for Destructive Assay (DA)
  - Samples are identified for Non-Destructive Assay (NDA)
- Samples may be collected for DA and shipped to the Safeguards Analytical Laboratory (SAL) near Vienna (NWAL-NetWork of Analytical Laboratories)
- Non-Destructive Assay is performed on location and often includes:
  - Verification of the Cerenkov Light (for spent fuel)
  - Active/Passive Coincidence Neutron Counting &
  - Gamma Ray Spectroscopy (for U-235 and Pu mass determination)

Nuclear Material Verification Systems

(Sources – IAEA, AECL, Channel Systems, ICXT, Bot Engr., and Canberra, 2009)

iCVD

DCVD



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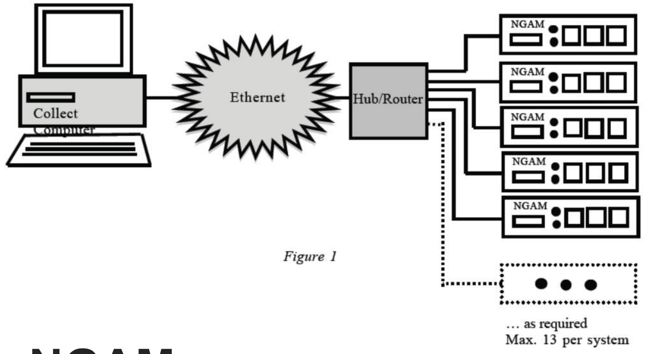
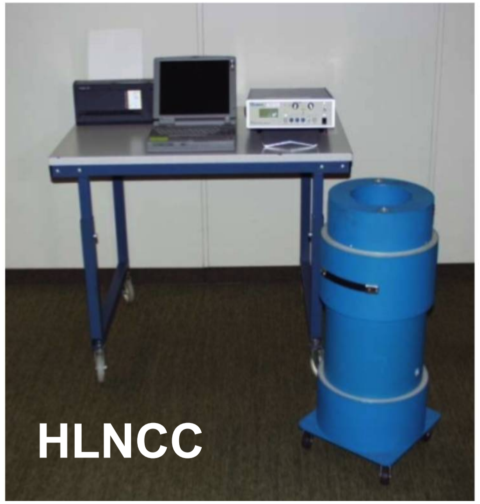


NGAM



MiniGRAND

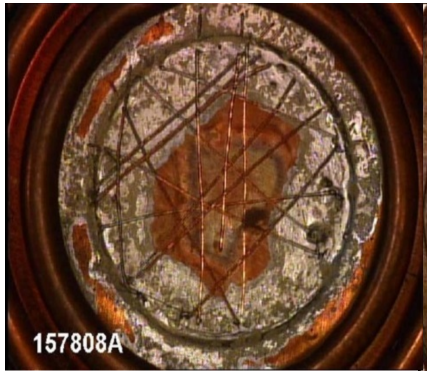
Other Important Safeguards Terms and Concepts *(INFCIRC/153 and IAEA Safeguards Glossary)*

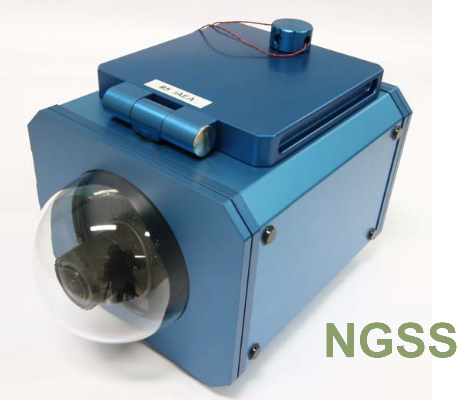
Containment and Surveillance (C/S)

- Complements Nuclear Material Accountancy (Example OSP)
- Includes nuclear material containment (seal), video surveillance, and related systems
- Maintains the continuity-of-knowledge (CoK) of safeguarded nuclear material and safeguards systems
- Are used as tampering indicating systems – i.e. to detect tampering with the nuclear material or safeguards system or detect undeclared nuclear material movements
- The enclosure/vault and seal wire/cable are integral parts of the containment system – their integrity must be assessed and ensured
- The seal and video surveillance has to be reviewed and evaluated by an inspector to draw a safeguards conclusion

Containment and Surveillance (C/S) Systems

GLASS SEAL





Other Important Safeguards Terms and Concepts *(INFCIRC/153 and IAEA Safeguards Glossary)*

Design Information Examination and Verification

- Design Information is…"information concerning nuclear material subject to safeguards under the agreement and the features of facilities relevant to safeguarding such material"
- Design Information (DI) must be provided by the State (SSAC) to the IAEA when a decision is officially made to construct a nuclear facility
- The State submits design information in the form of a completed IAEA Design Information Questionnaire (DIQ)
- The IAEA verifies this information by performing Design Information Examination and Verification (DIE/DIV)
- Initial DIE/DIV confirms the nuclear facility is built as declared. Continuous DIE/DIV confirms that operations are as declared – i.e. that its function or capacity has not been altered
- IAEA inspectors implement based on a DIV Plan for the life cycle of facility: using the facility DIQ, design drawings, visual observation, measurement tools to perform and incorporate the results of DIE/DIV

Other Important Safeguards Terms and Concepts *(INFCIRC/153 and IAEA Safeguards Glossary)*

Discrepancy
- An Inconsistency between the Inspector’s Observation and the Facility Operator’s Records and/or State Reports

Anomaly
- A Discrepancy involving more than 1 SQ of nuclear material
- Denial or restriction of IAEA access for Inspection
- Undeclared safeguards significant changes to the facility or operation

Material Balance Equation and Material Unaccounted For (MUF)

The size of the MUF (and Cumulative MUF) may indicate the protracted diversion of nuclear material - **Trend Analysis**

GOOD SAFEGUARDS:
What It Takes To Avoid Being Fooled?

Good safeguards: Complete set of interrelated measures covering all credible diversion paths– with some unpredictability.

• **Fudge the books**	***Records & Reports, Source docs; transit matching***
• **Take a bit at a time**	***Bias defects***
• **Take some at a time**	***Partial defects***
• **Substitute a dummy**	***Gross defects***
• **Present the same material**	***Containment/Surveillance***
• **Get around C/S**	***Remeasurement, Authentication***
• **Bring in other material**	***Borrowing measures***

Summary

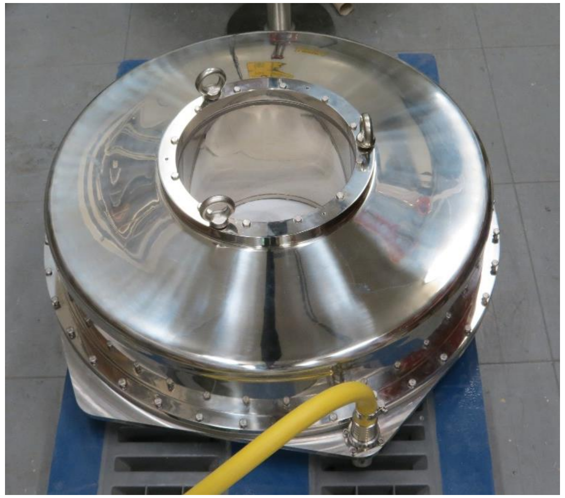
- The over-arching objective of IAEA Safeguards is the correctness, completeness, and timeliness of the State's declaration
- The application of IAEA Safeguards through direct inspections of a State's nuclear facilities is a key capability to assure they are meeting their obligation to the Treaty of Nonproliferation at declared facilities
- While there are many verification techniques available to the IAEA, there are still gaps to be addressed to allow for increases in efficiency and effectiveness that address quantification of nuclear material including future challenges with advanced reactors
- Emerging technologies such as digital twins could be a solution to improved safeguards monitoring at facilities with reduced inspector presence
- While not included in this talk, the detection of undeclared nuclear material and activities such as clandestine facilities is unequivocally the greatest challenge faced by the IAEA.

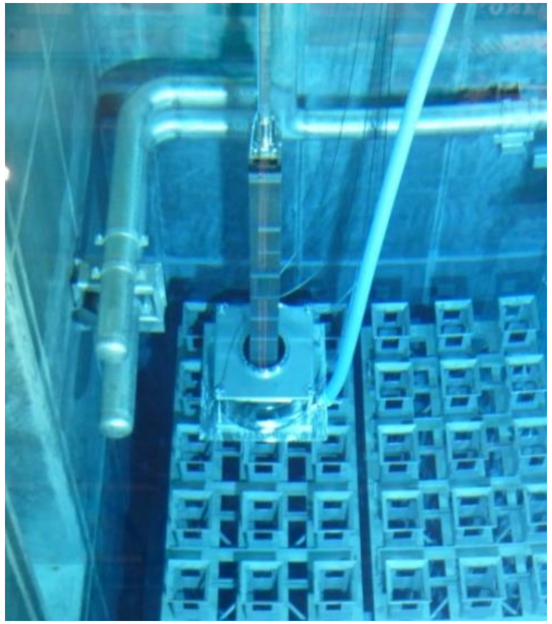
Environmental Sampling: The IAEA “Time Machine”

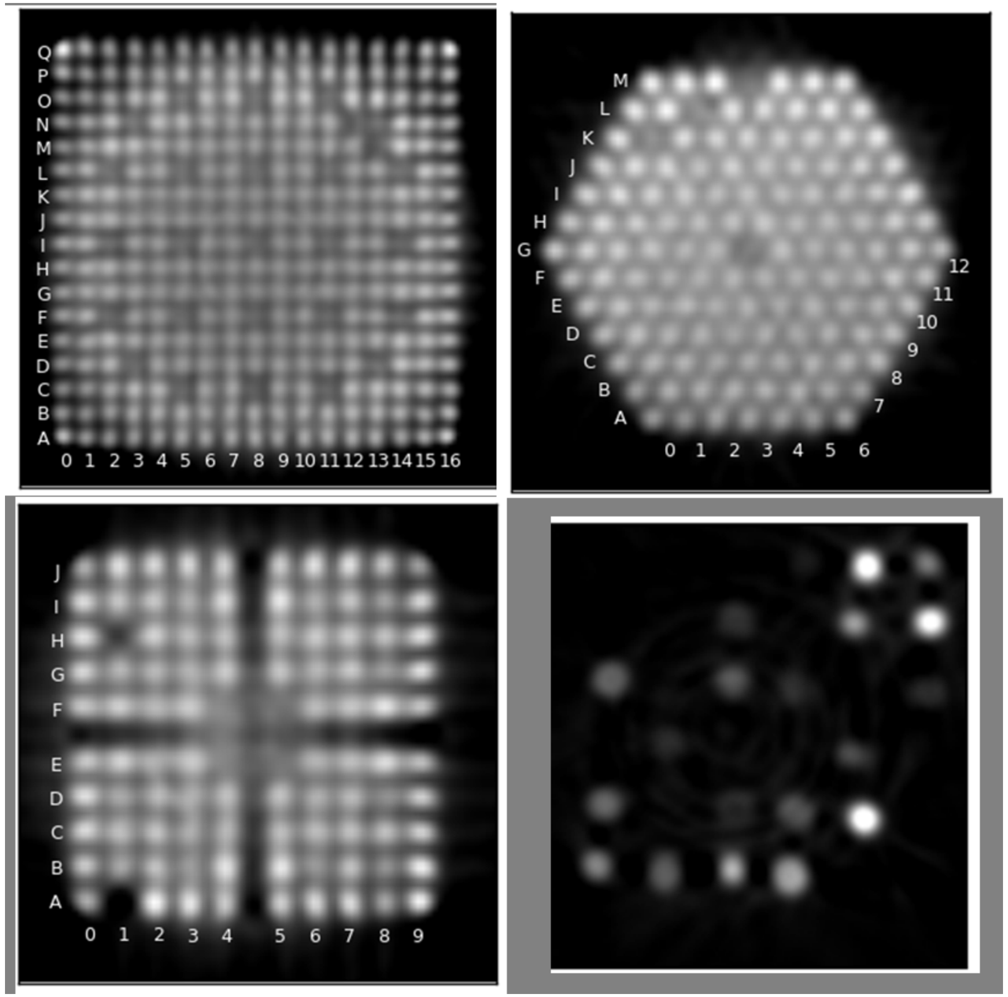
Current primary in-field tool used by the IAEA in support of INFCIRC 540

- Swipe sampling kits
- Samples sent to the IAEA Safeguards Analytical Lab (SAL) in Seibersdorf for analysis (NWAL)
  - Powerful destructive analysis tools
  - are applied
- Timeliness is an issue, this impacts an inspector’s effectiveness in the field
- *Best transparency for a State would be unattended environmental monitoring*

Passive Gamma Emission Tomography (PGET)





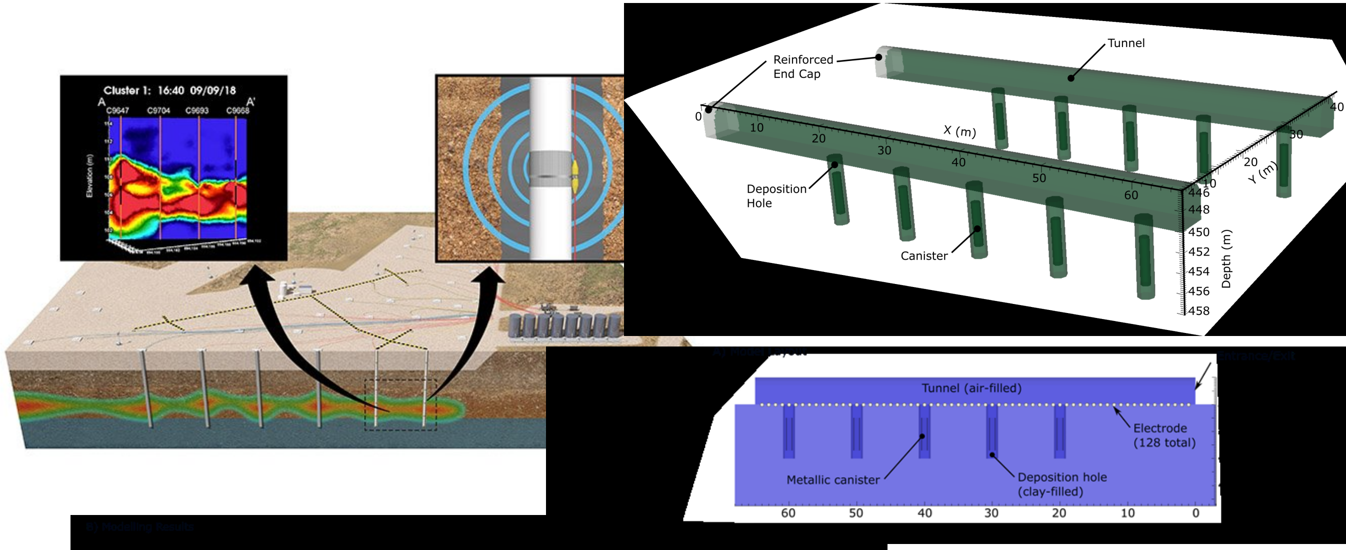


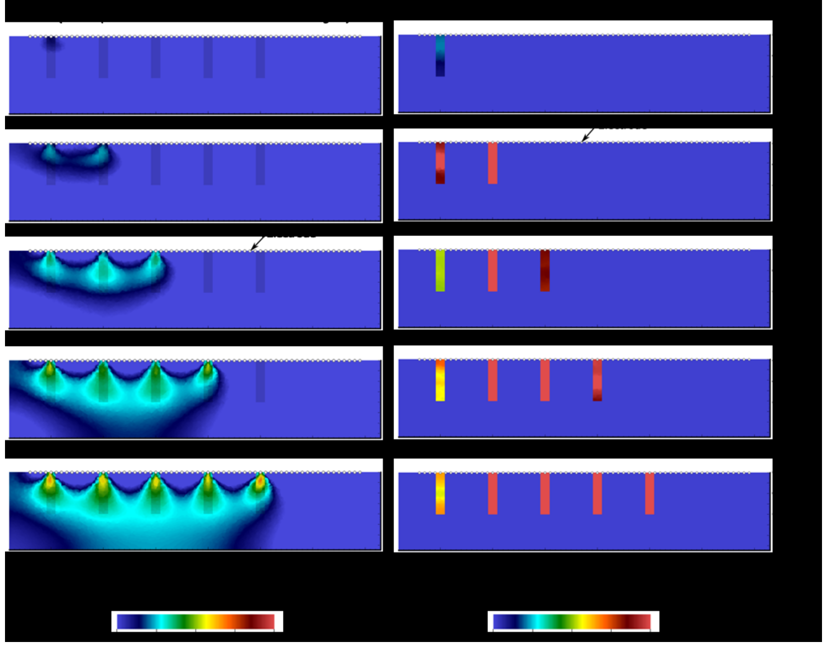
- PGET performs an emission tomographic measurement at an axial position of a spent fuel assembly and reconstructs an image of the relative pin activities.
- The PGET operates under water, either on the spent-fuel rack or on a stand on the pond floor. The fuel-handling device is used to move assemblies to the PGET for measurements.
- PGET can verify declarations at the single-pin level, and is the only instrument capable of verifying closed pin containers.

Point of Contact:
Tim White
Pacific Northwest National Lab
timothy.white@pnnl.gov
(509) 371-6806

Autonomous 3D Electrical Resistivity Tomography Monitoring for Geologic Repository Safeguards

- Safeguards Challenge: Continuous or periodic monitoring of waste canisters in a deep geologic repository
- Electrical Resistivity Tomography (ERT): Like MRI for rocks
- Autonomous 3D ERT can monitor for changes due to undeclared activities near deposition tunnels and waste canisters
- Currently performing a scoping study using detailed modeling of Onkalo design
- Exploring using planned/existing tunnels rather than adding boreholes
- Potential for providing unique insight into changes in the repository over time

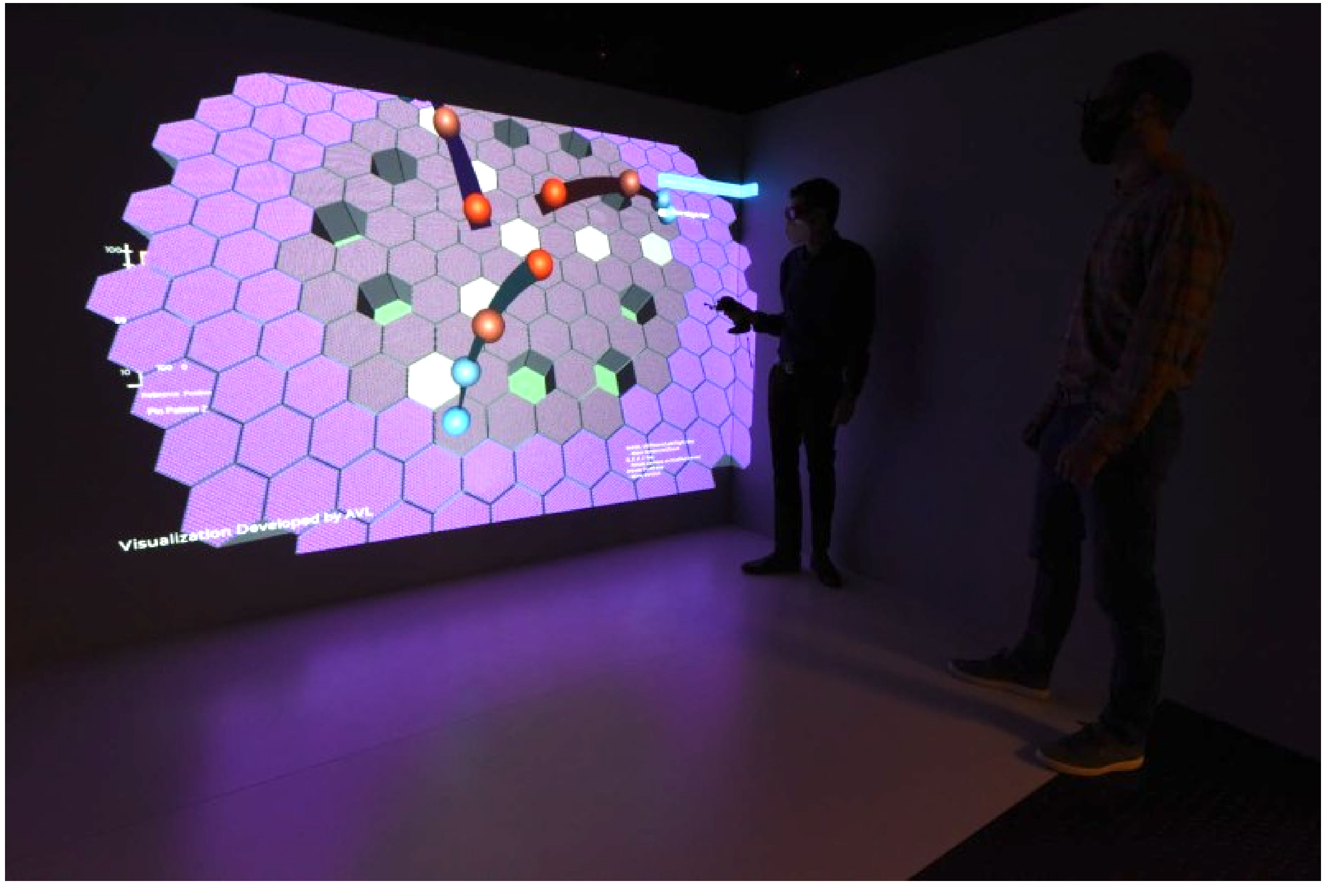




This work funded by DOE/NNSA Office of International Nuclear Safeguards

Digital Twin – A Paradigm Shift?

- Understanding functioning of a nuclear facility to the level of or even beyond that of the operator
- DPA can be conducted on a broad range of diversion and misuse scenarios and identify indicators of these events
- Sensors can be evaluated for their detection capabilities and gaps identified in time for required sensors to be added in a cost-effective manner Safeguards By Design (SBD).
- Once the DPA analysis is completed and the AI/ML algorithms validated, the twin and now be used for autonomous monitoring of the facility data streams.

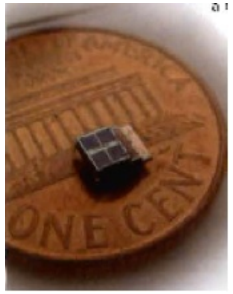


Visualization of a Sodium Fast Reactor Core using a High-Fidelity Digital Twin Model in a CAVE

Detecting Undeclared Activities Continuously

- Technology R&D should not be limited by
  - *Current IAEA inspection regimes*
  - *Current safeguards concepts*
  - *Current treaty limitations*

  Do not let the present stop the future

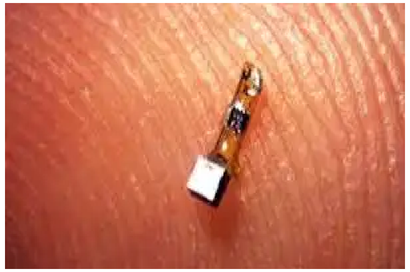


1-Solar cell, 1-Battery, 1-ARM Cortex-M3 processor: microprocessor uses less than 1 nanowatt – Univ. of Michigan **2010**

Ultimate Goal:

- Nano/Micro Sensors for nuclear & non-nuclear indicators, powered by environment, wireless and self organizing, remote data transmission (via cell phone towers?), inexpensive, and environmentally benign
- Small devices are also called motes.
- Size range: 20 micrometers up to a millimeter in size, based on microelectromechanical systems (MEMS)
- If they work together, often called Smart Dust

2020



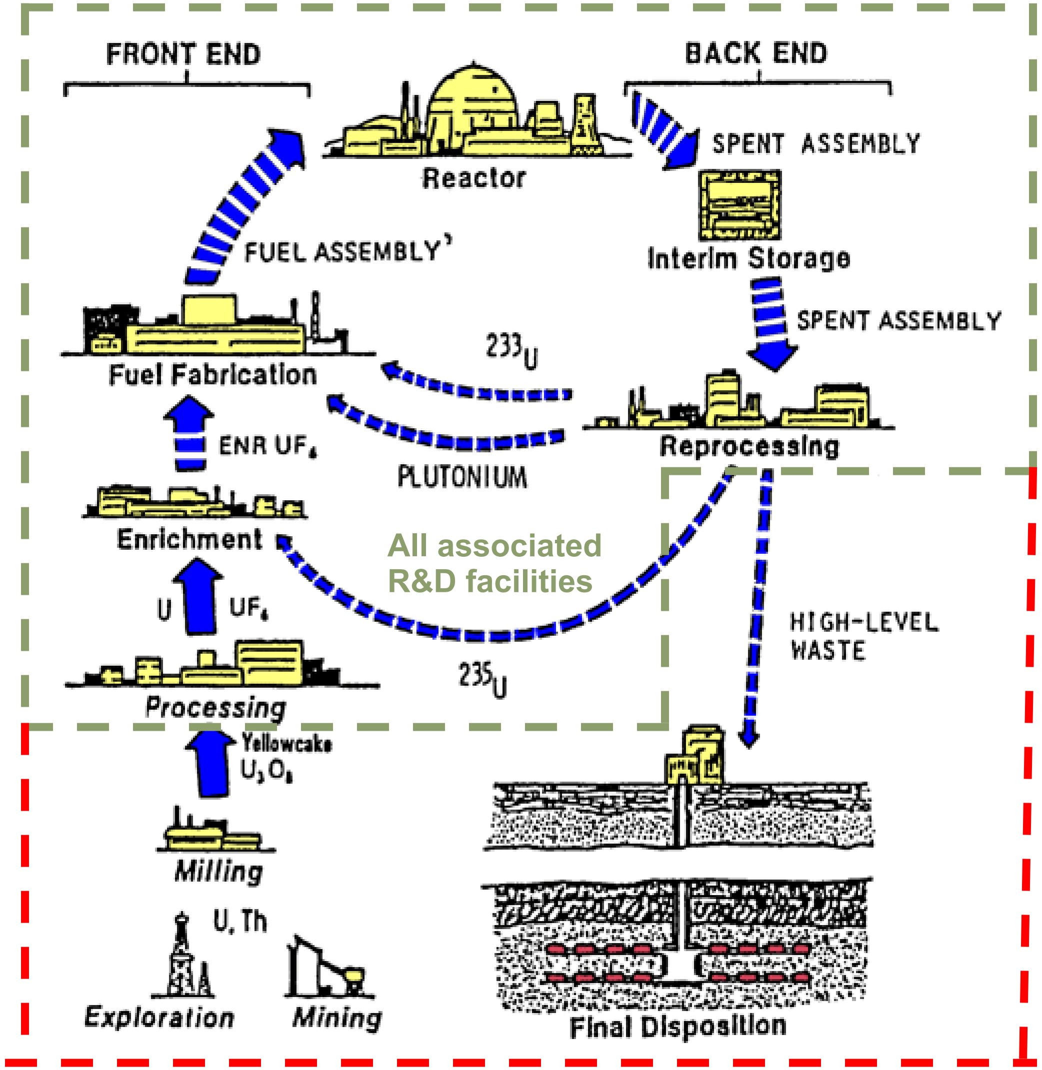
Questions?

Back Up Slides

Facility-Level Safeguards and the Additional Protocol

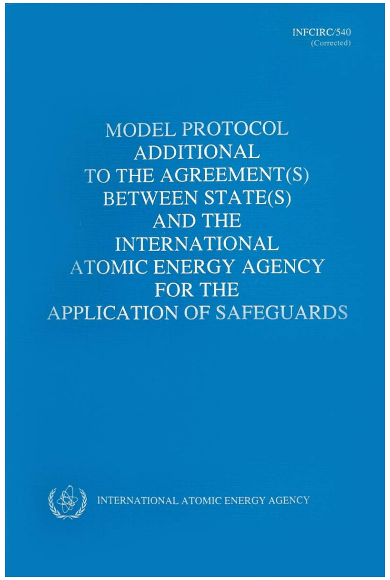
- To strengthen the Safeguards Regime, the IAEA and its Member States developed an Additional Protocol (AP – INFCIRC/540) to the Safeguards Agreement
- Signing is ***voluntary***
- It provides for :
  - Access to Information concerning the **complete nuclear fuel cycle and any type of location that might provide support** in the State, from mines to waste
  - Complementary Access to sites, facilities, and locations in the State
  - Use of Visual Observation, Radiation Detection, and Sampling to detect potential undeclared nuclear material and activities in the State

Location of Inspections (CSA-Black) & Complementary Access Areas (AP-All)



Coverage under a Comprehensive Safeguards Agreement

Additional Coverage Under an Additional Protocol



Complementary Access (CA) under Additional Protocols

The Protocol provides for IAEA inspectors to have "complementary" access to assure the absence of undeclared nuclear material or to resolve questions or inconsistencies in the information a State has provided about its nuclear activities

Advance notice in most cases is at least 24 hours. The advance notice is shorter - at least two hours - for access to any place on a site that is sought in conjunction with design information verification or ad hoc or routine inspections at that site

The activities carried out during complementary access could include examination of records, visual observation, environmental sampling, utilization of radiation detection and measurement devices, and the application of seals and other identifying and tamper-indicating devices